Environmental risk and the anchoring role of mobility rigidities*

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Abstract

We analyze the anchoring role of mobility rigidities following a news shock on environmental risk. Using an exhaustive registry of housing transactions in England between 2007 and 2014, we identify the impact of changes in perceived environmental risk by comparing property prices near nuclear facilities to those further away before and after the Fukushima nuclear accident. The average price drop amounts to 4.2%. There is significant heterogeneity, reflecting the different mobility rigidities faced by residents and workers. At-risk areas with highly-mobile labor structure undergo a more substantial price decrease after the catastrophe and an increase in deprivation. Such finding is further supported by the long-term patterns of residential flight after the opening of nuclear plants—a marked rise in deprivation is observed in neighborhoods where labor is mobile.

JEL codes: D80, Q51, Q53, R21, R23, R31.

Keywords: Household sorting; Hedonic prices; Nuclear risk.

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Hazardous risk may affect property prices in the vicinity of at-risk facilities (Davis, 2011; Muehlenbachs, Spiller, and Timmins, 2015). A direct effect derives from the agents' valuation of environmental risk. This valuation effect may be amplified through the movement of residents and workers, and the associated consumption and production externalities. For instance, richer residents may have high willingness-to-pay for environmental quality; they may avoid zones at risk, followed by productive industries and other endogenous amenities. This paper exploits a "news shock" about environmental risk and analyzes the role of mobility rigidities in tempering the responses in housing demand and neighborhood composition.

We isolate a rare experiment which strongly affected beliefs about nuclear risk and was not accompanied by changes in the institutional environment. This experimental variation is the Fukushima nuclear accident—the largest nuclear accident after the Chernobyl disaster—and its perception in England.[1] Given the large uncertainty about the risk related to nuclear facilities, agents should markedly revise their priors in the rare event of a catastrophe (Benoît and Dubra, 2013), leading to a local adjustment in housing demand.[2] This adjustment however depends on the capacity of workers and residents to move to safer areas. In order to illustrate the importance of mobility rigidities, we use spatial heterogeneity in local amenities, demographics and the production structure. We exploit (i) a well-identified experiment in the short-run and (ii) descriptive evidence of the rise in deprivation around nuclear facilities in the longer run. First, we identify the heterogeneous adjustment of housing demand and neighborhood composition after Fukushima, as a function of the extent to which local residents and workers are subject to relocation frictions. Second, we analyze the long-term patterns of residential flight after the opening of nuclear plants in the 1970s.

Using an exhaustive registry of housing transactions between 2007 and 2014 in England, we identify the impact of the Fukushima accident on housing demand from a comparison of at-risk neighborhoods with safer ones in a difference-in-differences specification. Our hedonic analysis proceeds in two steps. In a first step, we quantify the average impact on local housing markets. The housing price decrease is estimated to be around 4.2%. The effect is persistent throughout the post-Fukushima period, and is observed across a variety of specifications, e.g., using the neighborhoods of

[1] Alvin M. Weinberg, a nuclear physicist who pioneered reactor design, wrote after the Chernobyl accident, "a nuclear accident anywhere is a nuclear accident everywhere" (Weinberg, 1986). This observation is supported by the shift in public support for nuclear energy after Fukushima in countries such as France, Germany and South Korea (IPSOS, 2011), and after Chernobyl in the US (Smith and Michaels, 1987).

[2] An example of such revision in the case of rare events is Gallagher (2014), which provides evidence of high flood insurance take-up following large floods in the US.

large coal or gas-fired power plants as a control group.

In a second step, we explore how relocation rigidities may anchor neighborhood composition and mitigate the treatment effect. More specifically, we find that a less mobile labor force markedly mitigates the price drop in at-risk neighborhoods. We proxy the extent to which local labor supply is mobile by combining census data on the jobs of residents with measures of job mobility in various industries.[3] We also find supporting evidence that the price decrease is smaller in areas with larger moving costs for residents—proxied for instance by the difficulty to relocate in safer neighborhoods within the same commuting area or by previous migration. These findings are consistent with the observed heterogeneity in the elasticity of local employment, related to migration and commuting patterns (Monte, Redding, and Rossi-Hansberg, 2018).

Environmental risk triggers a flight among richer residents, which in turn may affect local communities through peer effects (Durlauf, 1996, 2004), agglomeration effects (Rosenthal and Strange, 2004), or preference-based segregation (Schelling, 1971; Anas, 1980; Card, Mas, and Rothstein, 2008). We provide some evidence for this residential flight and the role of mobility rigidities in tempering it. We first show a gradual response of neighborhood composition in treated locations after Fukushima.[4] Deprivation rises significantly between 2010 and 2019, especially so in locations with a highly-mobile labor structure. This adjustment in neighborhood composition may have an indirect effect on housing demand: housing demand should account for the equilibrium adjustments in population and production factors, and their associated externalities. The role of the local production structure is further supported by the descriptive analysis of long-term dynamics following the opening of nuclear facilities in the 1970s. Prior to plant opening, neighborhoods located in at-risk and safe areas of the future plants were similar in terms of neighborhood composition. From 1971 to 2001, population decreased in the vicinity of nuclear plants before stabilizing, a pattern mostly explained by the flight of richer residents. Relocation rigidities should however anchor neighborhood composition and moderate these dynamics. Indeed, these effects were mostly concentrated in at-risk areas with highly-mobile labor force.

Our findings provide insights into two major policy issues. They first highlight the (negative) neighborhood impact of nuclear risk, even in a historically-supportive

[3] This definition captures any underlying industry characteristics which lower job mobility, including, for instance, the rigidities associated with high firm relocation costs due to physical infrastructure (e.g., capital-intensive industries).

[4] We measure the adjustment in neighborhood composition after Fukushima using a deprivation index, i.e., the *English Indices of Deprivation*, which combines measures of household income, employment status, school quality, crime etc. The deprivation index is better described in Section 2.

environment (Poortinga, Aoyagi, and Pidgeon, 2013). Nuclear technology is expected to play an important role in the transition to low-carbon energy, and such expansion must be accepted by local communities. The revision of priors following a remote nuclear accident indicates large uncertainty about industrial risk (Huang et al., 2013).[5] Importantly, our findings further show the role of relocation rigidities in shaping the response of housing demand and neighborhood composition to a local shock (as in Monte, Redding, and Rossi-Hansberg, 2018).

The estimation of the impact of industrial risk on local communities presents a challenge. Hedonic analyses of the housing market are often contaminated by omitted variation. A large literature thus relies on news shocks, arguably orthogonal to local economic conditions, for identification. Fukushima was exploited as a major news shock about nuclear risk in a number of recent contributions, finding no effects in Sweden (Ando, Dahlberg, and Engström, 2017), non-significant or impermanent effects in the United States (Fink and Stratmann, 2015; Tanaka and Zabel, 2018), large but "short-lived" effects in China (Zhu et al., 2016), and large, persistent effects in Germany (Bauer, Braun, and Kvasnicka, 2017)—albeit related to the expected closure or phasing down of nuclear plants and the associated employment effects. Many elements—policy response, employment spillovers, insurance coverage, risk preferences or the functioning of housing markets—influence the hedonic response to environmental risk, which could explain the ambiguous findings of the literature.[6] Our findings of a large and persistent effect, comparable in size to the effect found using rental markets in Switzerland (Boes, Nüesch, and Wüthrich, 2015), is unlikely to be driven by an expected phasing down of nuclear power.[7]

The contribution of our study to the literature is (i) to document large spatial treatment heterogeneity in housing market responses, (ii) to relate this heterogene-

[5] Due to data limitations, we cannot directly observe priors about nuclear risk. Nonetheless, we find no evidence that residents incorporate the technological characteristics of the closest nuclear plant (e.g., past accidents or the technology of reactors) when revising their beliefs.

[6] A local increase in industrial risk perception may be accompanied by policy adjustments, such as compensation targeted towards at-risk populations or the premature closure of hazardous facilities (see Section A of the online Appendix for a comparison between the United Kingdom and other institutional settings). The United Kingdom offers an interesting context as it is one of the rare countries having shown "continued loyalty" towards nuclear power (Ramana, 2013)—notably by committing to the renewal of its nuclear plant fleet after the catastrophe. We find no evidence of any changes in policies that could have a specific impact on neighborhoods close to nuclear plants, such as governmental grants targeted toward these areas, and changes in safety regulations.

[7] In the United Kingdom, the life extension of most operational reactors was confirmed in December 2012, which did not come as a surprise and was not contested by major political parties. Moreover, we do not find a price rebound in at-risk neighborhoods around the announcement of December 2012; we do not find differential effects across nuclear sites with different local employment shares; we find a non-negligible price decrease around nuclear waste facilities—which are not susceptible to closure and exert no direct economic externalities on neighboring communities.

ity to the local heterogeneity in the mobility of residents and workers as induced by commuting, migration patterns and the nature of the local economic activity, and (iii) to validate this interpretation by looking at the evolution of neighborhood composition in the short run and in the longer run, as in Depro, Timmins, and O'Neil (2015); Lee and Lin (2018); Heblich, Trew, and Zylberberg (2018) for instance.

This paper contributes to two distinct strands of the literature. First, our paper investigates how the local characteristics of a neighborhood explain its response to an amenity shock. This relates to recent contributions studying (i) natural amenities, such as oceans, mountains and lakes, as an anchoring factor for neighborhood composition in the longer run (Lee and Lin, 2018), (ii) commuting patterns as factors shaping the heterogeneity in local employment elasticities across locations (Monte, Redding, and Rossi-Hansberg, 2018), (iii) moving rigidities and their role in tempering the market response to air quality (Bayer, Keohane, and Timmins, 2009). Our analysis of residential composition and our finding that the environmental disamenity induces a flight of residents in the longer run, mostly due to the outmigration of higher-skilled workers, relate to Banzhaf and Walsh (2008). The adjustment in population and neighborhood composition may induce a change in production spillovers (Haskel and Martin, 1993; Glaeser, 1998; Rosenthal and Strange, 2004) or local amenities (Glaeser, Kolko, and Saiz, 2001; Couture, 2013). Other spillovers governing residential sorting and the relocation of production include homophilous preferences (Schelling, 1971; Anas, 1980; Card, Mas, and Rothstein, 2008), peer effects within neighborhoods (Durlauf, 1996, 2004), the endogenous supply of amenities (e.g., school quality in Fernandez and Rogerson, 1996).

Second, the research contributes to the hedonic price literature estimating the amenity value of environmental factors. Recent papers have estimated the impact on residential sorting and housing prices of the following environmental (dis)amenities: hazardous waste (Gayer, 2000; Greenstone and Gallagher, 2008; Gamper-Rabindran and Timmins, 2013), shale gas wells (Muehlenbachs, Spiller, and Timmins, 2015; Gibbons et al., 2016), coal-fired power plants (Davis, 2011), wind farms (Gibbons, 2015), industrial pollution (Davis, 2004; Chay and Greenstone, 2005; Bayer, Keohane, and Timmins, 2009; Currie et al., 2015) and nature and wilderness (Gibbons, Mourato, and Resende, 2014). We relate closely to the specific strand investigating the cost of industrial risk in an hedonic framework, as in Gamble and Downing (1982); Folland and Hough (1991); Clark et al. (1997); Olsen and Wolff (2013); Bléhaut (2014). Our experimental design relies on a news shock, as in Gayer (2000); Davis (2004); Mastromonaco (2015), and the main experimental variation used as a news shock is a far-distant accident.[8]

The remainder of this paper is structured as follows. Section 1 discusses the context. In Section 2, we describe the data sources and the empirical strategy. Section 3 describes the average impact of the Fukushima accident and Section 4 presents our main findings, i.e., treatment heterogeneity along neighborhood characteristics. Section 5 briefly concludes.

1 Context

In this section, we briefly describe the main experimental variation, i.e., the Fukushima accident, its media treatment and its impact in the United Kingdom.[9]

The Fukushima nuclear accident On March 11, 2011, a major tsunami triggered by the Great East Japan Earthquake hit the Fukushima-Daiichi nuclear plant, leading to a failure of coolant systems and large radioactive leakages. This accident was given the highest level (Level 7) on the classification of the International Nuclear Event Scale, a level then only attained by the Chernobyl accident. The Japanese government responded by defining several zones: a *restrictive* area, 20 kilometers from the damaged plant, where evacuation was compulsory; an *evacuation-prepared* area between 20 and 30 kilometers, where residents were advised to stay indoors; and additional at-risk areas, where cumulative radiation might breach a safety threshold (20 millisieverts per year). In total, 150,000 residents were evacuated because of the Fukushima catastrophe (Japanese Government, 2011; Hasegawa, 2013). In July 2012, the Fukushima Nuclear Accident Independent Investigation Commission revealed that the regulatory institutions had overestimated the capacity of power stations to resist such an earthquake and tsunami and found that The Tokyo Electric Power Company (TEPCO) had failed to take adequate preventive measures.[10]

The incident raised concerns regarding the safety of all nuclear power stations across the world; the Japanese system was indeed considered as one of the safest. All countries with nuclear power announced inspections of their facilities (World Energy

[8] Domestic accidents trigger effects other than changes in risk perception, including the disruption of the local economy (Nelson, 1981; Gamble and Downing, 1982; Tanaka and Managi, 2016; Kawaguchi and Yukutake, 2017) and changes in risk preferences (Hanaoka, Shigeoka, and Watanabe, 2018).

[9] In Section A of the online Appendix, we provide a more complete description of the media treatment by local newspapers, the state of the nuclear fleet in England and Wales, and policy discussions in the United Kingdom as compared to the rest of the world.

[10] Following the accident, a large number of TEPCO executives were identified as former independent supervisors and similar conflicts of interest were detected in European countries. See "System bred TEPCO's cosy links to watchdogs", *The Financial Times*, April 20, 2011, and "Fukushima spin was Orwellian", *The Guardian*, July 1, 2011.

Council, 2012). The Fukushima accident had a massive impact on public support for nuclear power (IPSOS, 2011), often leading to policy adjustments or uncertainty about the continuation of nuclear programs (Davis, 2012; World Energy Council, 2012). Only a small group of countries unequivocally announced the continuation of their nuclear program in the aftermath of Fukushima, including the United Kingdom.

Impact in the United Kingdom The nuclear fleet in England and Wales included 15 operational nuclear reactors in 2010. With four additional reactors in Scotland, nuclear power accounted for about 16% of domestic electricity generation in the United Kingdom (IEA, 2011). All operational reactors but one were based on UK-specific technologies (Magnesium Non Oxidizing—Magnox—, or the Advanced Gas-cooled Reactor), whereas the Fukushima-Daiichi reactors were based on the second most common design of electricity-generating nuclear reactor in the world, the Boiling-Water Reactor (BWR). An overall assessment of risk inherent in each nuclear design is difficult as their merits in terms of safety depend on the accidents that are considered, the plant size and their vulnerability to surrounding hazards. However, the average nuclear plant in our sample is much smaller and newer than the Fukushima-Daiichi plant, and natural hazards, e.g., earthquakes, are much less frequent. Nuclear risk around Fukushima-Daiichi was probably higher than in at-risk neighbourhoods of the United Kingdom.

In principle, the extent to which residents would revise their beliefs about nuclear risk following Fukushima should account for similarities to and differences with the Japanese nuclear context, e.g., the respective regulatory institutions, reactor designs, and plant vulnerabilities to natural and man-made hazards. In practice, however, hypothetical scenario exercises are difficult to evaluate, even for seasoned experts. General public attitudes to nuclear power were found to be stable in the wake of Fukushima (Poortinga, Aoyagi, and Pidgeon, 2013). Anti-nuclear protests were mostly confined to anti-nuclear activists with limited support from the rest of the population, in stark contrast with Germany, Italy, Japan, or Switzerland.[11]

As a consequence of the general support for nuclear power, the United Kingdom confirmed its pre-Fukushima plans of reinforcing the nuclear fleet and transitioning to next-generation power plants. This position, showing "continued loyalty" to nuclear power (Ramana, 2013), clearly contrasted with that of many OECD coun-

[11] In January 2012, only 300 anti-nuclear protesters marched against plans to build a new nuclear power station at the Wylfa site. In February 2012, about seven protesters set up camp in an abandoned farm on the site of the proposed Hinkley Point C nuclear power station. On March 10, 2012, a year after the Fukushima nuclear disaster, a few hundred anti-nuclear campaigners formed a human ring around the Hinkley Point, Wylfa, and Heysham sites.

tries.[12] In June 2011, the government confirmed the list of eight sites—all adjacent to existing nuclear plants—deemed suitable to host new reactors by 2025. In February 2012, *Electricité de France* (EDF) applied to extend the life of all its Advanced Gas-cooled Reactors (AGRs), with the first two approvals granted in December 2012. In addition, the construction of two Evolutionary Pressurized Reactors (EPRs) at the Hinkley Point site received the go-ahead in March 2013. Overall, there was not the slightest expectation about a premature phase-out of operational plants.

The national support for nuclear power should not prevent *local* communities near nuclear facilities from adjusting their perception of nuclear risk. Local residents should update their beliefs about nuclear hazard, leading to a downward shift in housing demand. The overall support for nuclear power provides, however, assurance on the permanence of nuclear power plants in their neighborhood. Nuclear facilities generate large economic spillovers through the variety of services contracted by the power plant or their employees, or through local tax revenues. This employment effect may play a significant role in the wake of Fukushima (as in Germany, see Bauer, Braun, and Kvasnicka, 2017). Our context is useful in that it neutralizes direct fluctuations due to this employment effect.[13] Further deterioration in local economic prospects could only result from a risk-perception effect and the indirect equilibrium responses of residential sorting and local production.

2 Data sources and empirical strategy

This section describes our data sources, the main identification strategy, and provides important descriptive statistics.[14]

2.1 Data sources

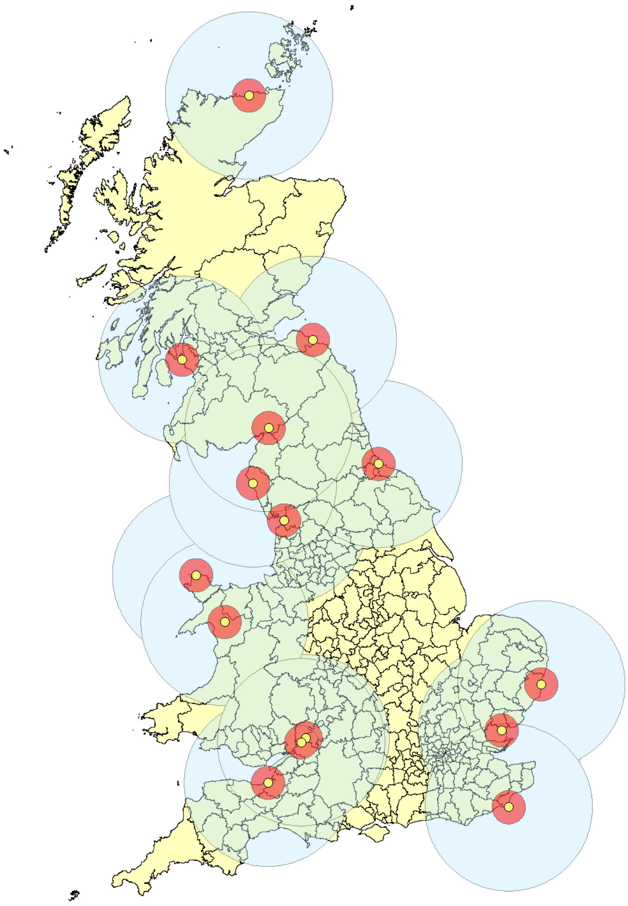
Nuclear facilities We restrict our analysis to England due to data limitations. The two major sources of potential radioactive contamination in England are nuclear power plants and nuclear waste sites.

[12]Chris Huhne, then Secretary of State for Energy and Climate Change, criticized European leaders for their haste in stopping nuclear development and reaffirmed the government support for nuclear power after the release of the Office for Nuclear Regulation Interim Report on the Fukushima accident (Weightman, 2011): "Having considered your findings, I see no reason why the UK should not proceed with our current policy: that nuclear should be part of the future energy mix [...].".

[13]Theoretically, the government could have compensated local communities for their (increased) perceived exposure to nuclear risk, making these areas attractive to households with a low valuation of safety. Again, the absence of any such policy response or discussion in Parliament reduces concerns about such policy effect.

[14]Section B of the online Appendix presents a comprehensive description of the data.

Figure 1. Map of nuclear power sites in Great Britain (2010).



Note: This map shows the distribution of nuclear sites (yellow dots) that host one or several active nuclear plants or/and plants used as nuclear waste sites, and our definitions of treated (dark red) and control (light blue) areas in Great Britain (2010). Note that six of the displayed nuclear sites are in Scotland or Wales, and thus absent from our final sample apart from the one which is sufficiently close from the borders for some LSOAs in England to be treated.

In March 2011, 15 operational reactors over 8 active nuclear power plants could threaten neighborhoods in England (see Figure 1). We collect information on the location of active and inactive nuclear power plants, their capacity, the number of operating reactors, the start of their commercial operation, the date of their (expected) closure, the technology (Department of Energy & Climate Change and the International Atomic Energy Agency PRIS database), the number of workers employed in each nuclear site from the plant operator website, and a list of historical accidents (e.g., cracks). Radioactive wastes come from three main sources: the generation of electricity in nuclear power plants, nuclear weapon programs, and the usage of radioactive materials in industry, medicine, and research. They are classified into three categories according to the nature and quantity of radioactivity they contain and their heat-generating capacity. High Level Wastes (HLW) are wastes with high levels of radioactivity and they require advanced facilities due to heat generation. Intermediate Level Wastes (ILW) are highly radioactive but do not require cooling devices. Low Level Wastes (LLW) are low in radioactivity, and no advanced storage facilities are needed.[15]

Housing data Our main empirical analysis draws on Land Registry transaction data between January 2007 and December 2014. Under the Land Registration Act 2002 and the Land Registration Rules 2003, Land Registry registers all sales and changes in ownership rights (mortgage, lease or right of way) in England. The transaction data are exhaustive, and a few property characteristics are recorded, i.e., price, postcode, type of property (flat, terraced house, detached house), and whether the property was built during the past 10 years.

We also rely on a separate data source based on new mortgages issued by Nationwide—the second largest mortgage company in the UK—between January 2007 and December 2013. The Nationwide dataset includes a wider range of controls for property characteristics (e.g., the construction date, the number of bedrooms, the size in square meters) but only accounts for 15% of sales. We use the Nationwide data in robustness checks cleaning for property-specific characteristics.

Neighborhood characteristics We collect data on neighborhoods to study how the housing market reaction to a shock varies alongside baseline neighborhood characteristics. These characteristics are also used to verify that variation in housing demand between neighborhoods before and after the accident is not due to price trends which correlate with specific neighborhood features around nuclear plants. Throughout the remainder of this paper, a "neighborhood" will be a very specific geographic unit: a Lower Super Output Area (LSOA), as delineated in the 2011 Census of England and Wales. LSOAs are geospatial statistical units in England and Wales, comprising between 400 and 1,200 households and covering 3-4 square kilometers on average.

First, we gather information on socio-economic and demographic characteristics of households. From the 2011 Census of England and Wales, we construct measures of housing quality, number of schooling years, ethnic and religious compositions, housing tenure, the number of children per household, the unemployment rate, and

[15] We provide additional information about nuclear facilities and waste sites in Section A of the online Appendix. For instance, we document the packaged volume for each waste category, the location, and the site owner of each of the 44 radioactive waste sites in the United Kingdom. These sites are in 34 distinct locations, about half of those being decommissioned or operational nuclear power plants.

whether the LSOA is classified as urban or rural. In addition, we use the *English Indices of Deprivation (2004, 2007, 2010, 2015, 2019)*, constructed by the Social Disadvantage Research Centre at the University of Oxford, in order to characterize the evolution of neighborhood composition and neighborhood amenities after the Fukushima accident. The deprivation index summarizes different forms of neighborhood deprivation captured by household income, (un)employment, crime, school quality, barriers to housing and services, living environment, health and disability.

Second, we construct measures of relocation rigidities at the level of an LSOA. Using a representative sample of workers with data on job history for 50 years after World War II, Booth, Francesconi, and Garcia-Serrano (1999) document job mobility across industries in the United Kingdom. Workers change jobs more often in industries such as (light) manufacturing, distribution and finance, and some occupations—managers, professionals, clerks, and the self-employed—have slightly higher turnover rates. From the 1971 and 2011 Censuses, we measure the share of high-mobility industries and high-mobility occupations based on Booth, Francesconi, and Garcia-Serrano (1999) for all LSOAs both in 1971 and in 2011. We also use the 2011 Census to construct measures capturing the commuting patterns within an LSOA and recent flows in and out of the LSOA. The exact construction of these quantities is made explicit in Section 4.

Third, we collect data on amenities at the LSOA level, such as public services, schools, national parks, and historical heritage sites. These data are obtained from overlaying maps of LSOAs with (i) the Point of Interest data provided by the Ordnance Survey, (ii) listing data from the National Heritage List for England (NHLE), (iii) historical pollution data and past presence of coal-burning factories (Heblich, Trew, and Zylberberg, 2018), SO_2 concentration measured by the Department for Environment, Food and Rural Affairs. We also construct a set of basic topographic indicators for each LSOA (elevation, latitude, longitude, proximity to cooling water, distance from and orientation with respect to the closest nuclear plant).

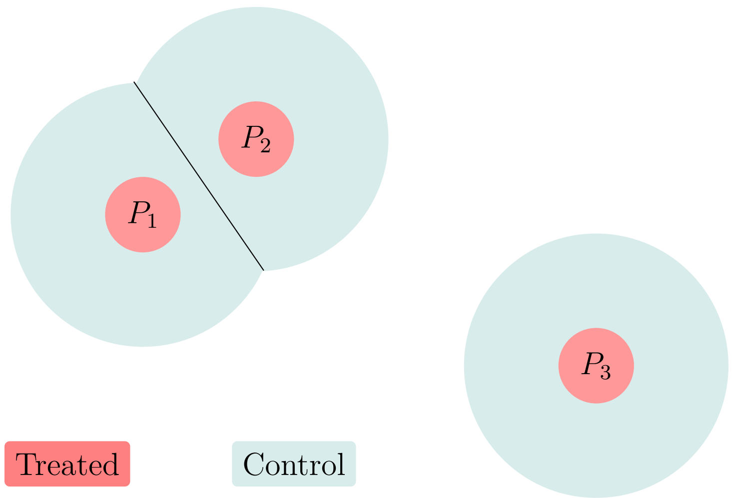
2.2 Empirical strategy

Our difference-in-differences strategy requires us to assign a spatial treatment and a time treatment. We rely on the Fukushima-Daiichi evacuation process and their characterization of the evacuation zone in order to define the spatial treatment.[16] While the unit of observation is a transaction, which can be geolocated at the post-

[16]The evacuation process was abundantly discussed in the media, e.g., “Fukushima nuclear plant blast puts Japan on high alert”, *The Guardian*, March 12, 2011. “[Japanese] authorities are evacuating tens of thousands of residents living within a 12-mile [20-kilometer] radius of the Fukushima-Daiichi plant.”

code level, we define our spatial treatment at the level of an LSOA. A transaction i will be treated (resp. in the control group) if the transacted property is located within a treated LSOA (resp. a control LSOA). An LSOA l is defined as treated ($T_l = 1$) if the median distance between the LSOA postcodes and the nearest nuclear site is lower than 20 kilometers. An LSOA will be in the control group ($T_l = 0$) if the median distance between the LSOA postcodes and the nearest nuclear site is between 20 and 100 kilometers. The analysis will be cleaned from fluctuations in property prices specific to the wider area around a given nuclear plant; for a given LSOA l, we label the identity of the closest nuclear site or, equivalently, its "zone of influence", with the index z. Figure 1 displays the treated and control areas for all nuclear plants, and Figure 2 illustrates the construction of the treatment and the zone of influence when a location may be within 100 kilometers of more than one nuclear plant.

Figure 2. Treated and control groups around nuclear plants P_1, P_2, and P_3.



Note: Treated areas are defined as all LSOAs whose median distance between its postcodes and the closest nuclear power plant is less than 20 kilometers. Control areas are defined as being between 20 and 100 kilometers from a nuclear power plant and not in any other evacuation zone. LSOAs are associated to the closest nuclear plant, denoted by z and labeled by P_z on the figure.

We define January 2007–March 2011 as the pre-Fukushima period ($F_t = 0$ where t is a month/year), and April 2011–December 2014 as the post-Fukushima period ($F_t = 1$). The main empirical strategy is a difference-in-differences specification,

$$p_{ilzt} = \alpha + \beta T_l \times F_t + \gamma \mathbf{X}_{ilt} + \delta \mathbf{X}_{ilt} \times F_t + \nu_l + \sum_z \delta_z \times F_t + \varepsilon_{ilzt}, \qquad (1)$$

where β is the main coefficient of interest. The dependent variable, p_{ilzt}, is the (log) price of a transaction i located within LSOA l and occurring in month/year t. We consider the vector $\mathbf{X}_{ilt}$ and its interaction with the post-treatment dummy as the *extended controls*. The vector $\mathbf{X}_{ilt}$ includes the LSOA deprivation score in 2010 and transaction characteristics: whether the property is new; whether it is a flat, a terrace house, a semi-detached house, or a detached house. This vector of characteristics is also interacted with a post-treatment dummy to control for differential trends in housing demand along neighborhood quality or transaction characteristics.[17] The set of zone-of-influence dummies × the post-Fukushima dummy, $\{\delta_z \times F_t\}_z$, accounts for changes in the housing market over time in the larger area (0-100 km) around each nuclear plant. In the baseline specification, we add LSOA fixed effects, ν_l, in order to reduce noise related to time-invariant unobserved characteristics.

The empirical strategy relies on the following theoretical intuition. There exist large commuting zones, corresponding in practice to our zones of influence; these zones are affected by different dynamics in housing demand and housing supply. Within these commuting zones, there exist many locations which are imperfect substitutes, either because of idiosyncratic preferences, commuting costs induced by the different workplace locations of agents or different valuations of local amenities. The distance to the nuclear plant is one of these local (dis)amenities, and we interpret the Fukushima accident as a shift in the valuation of this disamenity. Our main object of interest is the shift in housing demand associated with this valuation shift. The relationship between this theoretical object and the parameter β in specification (1) relies on a few conditions. First, we consider that housing supply is not elastic over a period of 3-4 years—the average time difference between pre-Fukushima and post-Fukushima transactions in our sample.[18] Second, the analysis needs to be conditioned on permanent differences across locations, captured in the empirical analysis by the LSOA fixed-effects ν_l. Third, the analysis should be orthogonal to the price dynamics across commuting zones, hence the time-varying zone fixed-effects $\{\delta_z \times F_t\}_z$ and the difference-in-differences approach comparing the most affected locations to the least affected locations within a commuting zone. Fourth, the difference-in-differences specification implies that we assume away a shift

[17] Transaction characteristics may be considered bad controls as the selection of properties into transactions may be affected by the treatment. However, (i) we are mostly interested in the price response conditional on property characteristics, and (ii) we do not find differential changes in observable transaction characteristics along treatment.

[18] Evidence suggests that the elasticity of housing supply is low in the United Kingdom due to heavy restrictions regulating the destruction/renovation of the existing housing stock and land availability (see Malpezzi and Maclennan, 2001; Caldera and Johansson, 2013, for an estimation of long-run elasticities). We verify in an unreported test that there are no differential changes over time in the construction of recent properties (2010–2015, as reported by the Valuation Office Agency) in treated areas relative to non-treated areas. Note, however, that movements in housing supply include the conversion of existing residential units—which would not be observed within this dataset.

in housing demand provoked by the Fukushima accident in control locations.[19]

We consider a set of alternative specifications to the baseline specification (1) in robustness checks. Our treatment assignment rule is that a transaction is treated if the property is located in a treated LSOA, i.e., an LSOA with more than half of its postcodes that are within the 20-km evacuation zone of a nearby nuclear plant. While LSOAs are fairly small, being on average about 3-4 square kilometers, this treatment assignment may ignore within-LSOA heterogeneity in treatment exposure (Gamper-Rabindran and Timmins, 2013).[20] An alternative assignment is to consider that a transaction is treated if the centroid of the associated postcode is located within 20 km of a plant, and non-treated if the centroid of the associated postcode is between 20 and 100 km of the plant (without being within 20 km of any other plant). In addition, we consider alternative assignments of transactions to treatment and control groups, for instance by using alternative bandwidths or considering buffer zones between treated and control areas. One important alternative specification restricts the control group ($T_l = 0$) to LSOAs within a hypothetical evacuation zone of 20 kilometers around coal or gas-based power plants in order to separate the change in nuclear-risk perception from that in industrial-risk perception and control for possible changes in energy policy that are concomitant to the accident.

The previous baseline specification provides an average estimate of the treatment effect on housing demand. We document heterogeneous treatment effects using two strategies. First, we exploit our transaction-level data to examine how the housing price response to the Fukushima accident varies across quantiles of the property price distribution. Second, we estimate how LSOA characteristics or plant charac-

[19]Our main estimate can be interpreted as a lower bound of the true demand shift for at least two reasons. First, supply may not be perfectly inelastic. Second, the control areas close to the plant evacuation zones may also be negatively impacted by a revision in priors about nuclear risk. These control areas may also be indirectly affected through the residential demand of residents from treated areas. The bias induced by the use of difference-in-differences in hedonic settings is being discussed in recent contributions (Kuminoff and Pope, 2014; Banzhaf, 2019). Banzhaf (2019) shows that the difference-in-differences estimate is a lower bound of the welfare effect when the Stable Unit Treatment Value Assumption is violated. To alleviate the concern that the control group might be impacted by the accident, we consider 'doughnut' specifications with a buffer zone between treated and control areas in robustness checks. One argument in favor of control areas not being affected too markedly by this spillover is that they are 24 times larger than treated areas, and slightly more densely populated on average.

[20]The baseline specification, by defining treatment at the LSOA level, partly ignores the geography of an LSOA. A few remarks are in order. First, the area of the average LSOA is small compared to our treated zone—one LSOA covers about one percent of the evacuation zone of one nuclear plant on average. Second, controlling for the LSOA size by adding the LSOA area (or a dummy for rural LSOAs) interacted with a post-Fukushima dummy as controls in specification (1) does not change our main findings. Third, we do not find large heterogeneity in the treatment effect within LSOA: there is no discontinuity in the treatment effect across postcodes of LSOAs bordering the 20 km evacuation zone; the effect of the distance between a postcode and the nuclear plant, controlling for the evolution of prices at the LSOA level, is small.

Table 1. Descriptive statistics in 2010.

Sample	All	$T_l = 1$	$T_l = 0$
Observations	404,157	22,518	381,639
	Housing market		
Average price	254,249	182,856	258,461
fraction of new buildings	.054	.055	.054
fraction of flats	.203	.104	.208
	Deprivation scores		
Income rank	.548	.545	.548
Employment rank	.556	.496	.560
	Distance to nuclear facilities		
Distance to nuclear plants	63.58	13.77	66.52

Note: A unit of observation is a transaction. T_l is equal to 1 for all transacted properties located in LSOA l within the potential evacuation zone of a nuclear power plant, and to 0 for all transacted properties in a band of 20-100 kms of a nuclear plant (while not being in any evacuation zones). Transaction prices are expressed in pounds. The deprivation scores are the percentile in the distribution over all the LSOAs in England. A rank of 1 (resp. 0) means that the LSOA has the lowest (resp. highest) deprivation score in England.

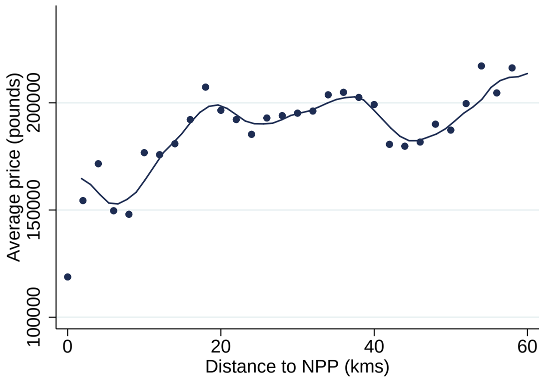
teristics affect the shift in housing demand. To do so, we re-estimate Equation (1) with interactions between LSOA or plant characteristics, A_{lz}, and the spatial/time treatments. The coefficient before the triple interaction, $A_{lz} \times T_l \times F_t$, captures treatment heterogeneity along A_{lz}. The role of the local production structure, commuting or migration patterns, consumption amenities (e.g., nature, schools, public services), topography characteristics, and a set of plant characteristics (e.g., capacity, technology, past accidents) will be studied.

2.3 Descriptive statistics

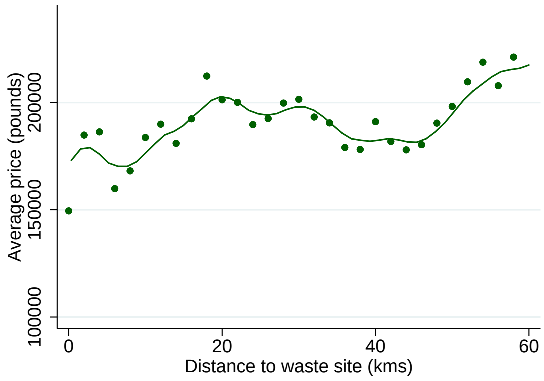
Table 1 provides summary statistics for transactions in treated and control LSOAs in 2010. There are few differences between transactions of properties located in the potential evacuation zone of a nuclear power plant and peripheral LSOAs. The average price is markedly lower in neighborhoods closer to nuclear power stations, which may reflect a lack of employment opportunities (see the LSOA *employment* deprivation rank). This wedge indicates higher deprivation which—as we document in the following sections—results from the opening of nuclear plants in the 1970s and the later dynamics of residential sorting. The price gradient along distance to the nuclear facilities is more apparent in Figure 3 and shows a sharp decrease starting 20 kilometers from a nuclear plant—and a similar pattern around nuclear waste sites.

Pre-Fukushima differences in average price levels between areas close to nuclear sites and those more distant are expected. However, these differences in levels are not directly threatening our difference-in-differences identification strategy. A threat to the identification strategy would arise if housing markets in neighborhoods close

Figure 3. Average transaction price as a function of distance to nuclear plants and waste sites.



(a) Nuclear plant.



(b) Waste site.

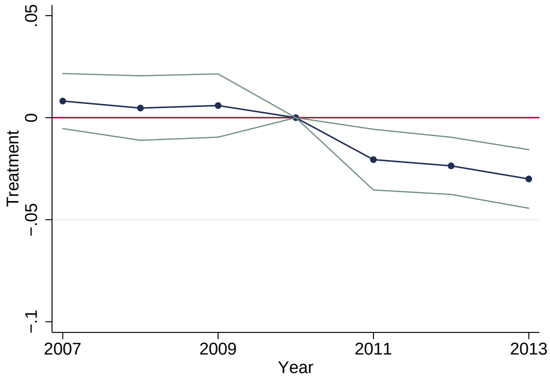
Note: This figure displays the average transaction price as a function of distance to the closest nuclear plant (left panel) and waste site (right panel) over the period January 2007–December 2014.

to a nuclear plant were to follow different trends than those further away. We provide a visualization of these possible differential trends in panel (a) of Figure 4, where we display the estimates of the price gap between treated and control areas in each year over the period 2007–2013. More precisely, we estimate a variation of Equation (1) using the interactions of the spatial treatment T_l and year dummies. We use Nationwide data to control for a large set of property characteristics in panel (a) and the measure of neighborhood deprivation in panel (b). As apparent from Figure 4, we find little support for the existence of differential trends before the accident. Market adjustments to the catastrophe occur abruptly before 2012 and remain stable afterwards.

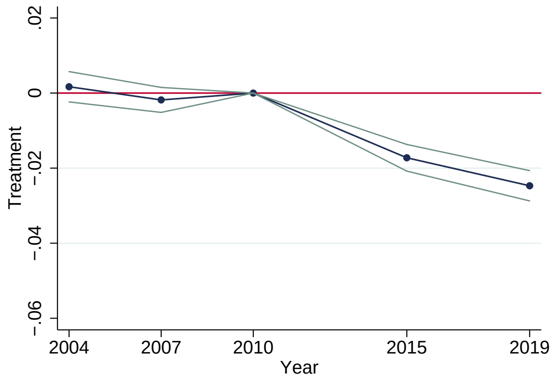
3 Average effect of the Fukushima incident

This section is organized as follows. First, we analyze how the news shock affects property prices in our benchmark specification. We also explore the persistence of the effect and changes in the price distribution. Second, we provide a series of robustness checks to support our benchmark estimates. In particular, we show the robustness of our estimates to (i) alternative treatment definitions and an alternative control group based on the proximity to other industrial parks, (ii) differential trends depending on local socio-economic characteristics, and (iii) the addition of a large set of transaction controls. We then document how the variation of the Fukushima impact on housing prices relates to plant characteristics.

Figure 4. Treatment effects per year (event-study approach)—housing demand and neighborhood composition.



(a) Transaction prices.



(b) Deprivation rank.

Note: Panel (a) displays the yearly treatment effects for transactions recorded in Nationwide over the period April 2007–December 2013. 2010 is the reference year. For each year, observations are transactions made between April of that year and March of the following year, March 2011 is excluded. Panel (b) displays the yearly treatment effects for deprivation rank—which ranges between 0 (most deprived LSOA) and 1 (least deprived LSOA)—in 2004, 2007, 2010, 2015 and 2019. 2010 is the reference year.

3.1 Baseline results

A shift in housing demand We first quantify the average price response to the news shock on nuclear risk. In Table 2, we report the estimates of specification (1) over the period January 2007–December 2014 for the (log) price. We estimate three variations of specification (1). In column 1, we report estimates without LSOA fixed effects and without controlling for transaction controls. In column 2, we add LSOA fixed effects and we add the set of extended controls in column 3.

Table 2. Effect of the news shock on property values.

	(1)	(2)	(3)
Price	-.0346	-.0371	-.0417
	(.0049)	(.0033)	(.0033)
Observations	3,739,200	3,739,200	3,739,200
LSOA fixed effects	No	Yes	Yes
Extended controls	No	No	Yes

Note: Standard errors, clustered at the LSOA × month level, are reported in parentheses. Each cell displays the result of a separate regression (specification 1). The unit of observation is a transaction. We only report the difference-in-differences coefficient, i.e., the coefficient before the spatial treatment interacted with a post-Fukushima dummy. All specifications include post-Fukushima dummy × zone dummies. See Section 2 for a definition of the set of *Extended controls*, including notably the interactions between transaction characteristics/LSOA deprivation score and the post-Fukushima dummy.

We find a price decrease of about 4.2% in the proximity to active nuclear plants after the Fukushima accident in our preferred specification (column 3).[21] The reported estimates are large and economically significant because treated zones represent about 5% of the housing stock in England. The associated drop in the value of the property stock near nuclear facilities would be around 9.2 billion pounds—which corresponds to a 0.2% decrease in the value of the aggregate housing stock. These computations however assume away spillovers and other equilibrium effects affecting the relative dynamics of housing markets between treated and control areas (a usual concern with hedonic specifications in difference-in-differences, see Kuminoff and Pope, 2014; Banzhaf, 2019).

In order to shed light on the changes in neighborhood composition induced by the treatment,[22] we rely on the English Indices of Deprivation constructed in 2004, 2007, 2010, 2015, 2019, and we run a specification at the LSOA $\times$ wave level, with the deprivation rank as the dependent variable and the spatial treatment interacted with wave-fixed effects as the explaining variables.[23]

We display the wave-specific treatment effects in panel (b) of Figure 4: there is an increase in deprivation in at-risk zones relative to control areas—an increase which is not preceded by differential trends before the shock. This effect is very large: the treatment effect translates into a shift of about 0.02 in deprivation rank—which ranges between 0 (most deprived LSOA) and 1 (least deprived LSOA).[24] We interpret this effect as being driven by an adjustment of neighborhood composition.

[21]The number of transactions per LSOA decreases by about 1.4% (see Appendix Table A1), and this quantity drop, coupled with the price decrease, implies a drop in the aggregate expenditure committed in new contracts of about 5.6%. The relatively modest decrease in the number of transactions (1.4%) compared to the price drop (4.2%) points to a low price-elasticity of housing supply: the shift in demand mostly translates into a decrease in price. This result stands in stark contrast with studies having documented a rest-vacancy effect, i.e., households refusing to lower their prices and waiting for a future rebound (Bléhaut, 2014).

[22]We choose to document socio-demographic changes through the evolution of deprivation indices rather than through imperfect measures of turnover. For instance, theoretical predictions about the number of housing transactions are not so clear in models of competitive housing markets: Turnover relates to the stability of the *relative* valuation of neighborhoods by the different residents. In dynamic models of residential choice, the latter would depend on the structure of preference shocks for neighborhoods and their persistence over time. With idiosyncratic preference shocks in each period, for instance, there would already be a large turnover rate at the steady state. In practice, adjustments in the rental market may also lead to an under-estimation of turnover.

[23]There is one caveat associated with the construction of deprivation indices. These indicators rely on raw data collected at different frequencies, and the construction of a few sub-indices requires to extrapolate the evolution of the raw indicators (for instance, population counts). This extrapolation implies that deprivation indices may imperfectly capture unpredicted changes over time, as the one induced by Fukushima. Note that many deprivation sub-indices heavily rely on higher-frequency data (e.g., employment, school, crime), which alleviate this issue.

[24]We verify in unreported tests that the negative treatment effect is large and negative for the following deprivation sub-indices: income, employment, health, crime. The treatment effects on the education, barriers to housing and environment sub-indices are of a much lower magnitude.

Richer residents may indeed have a high willingness-to-pay for environmental quality and the news shock affects their neighborhood valuation disproportionately. A flight of richer residents is in line with the theoretical literature on neighborhood sorting and amenities (Banzhaf and Walsh, 2013). This response should induce differential elasticities along the price distribution, as we see next.

Treatment heterogeneity In our baseline, the treatment is defined at the LSOA level while using transactions as observation units. We run a specification similar to our baseline, but we now define the treatment at the postcode level to show that the aggregation of treatment at the LSOA level is not an issue (see column 1 of Appendix Table A2). A postcode is considered treated if its centroid is located within 20 km of a plant, and non-treated if between 20 and 100 km of the plant (without being within 20 km of any other plant). Our main estimate of interest is unchanged. In column 2, we report a specification where we identify a potential within-LSOA effect, i.e., we control for time-varying fixed-effects at the LSOA level and use the postcode treatment—a specification which can be understood as a discontinuity design at the 20 km border. We find no discontinuity at the 20 km border: our treatment definition is justified by the extent of evacuation zones, but the treatment effect is probably quite continuous at the border. Finally, we report a specification with a treatment defined at the postcode level and with postcode fixed effects in column 3. The estimates are, again, similar to baseline estimates.

We estimate specification (1) across different quantiles of the LSOA property price distribution to test for the presence of non-linear effects on (log) housing prices. We report the results of this specification in Appendix Figure A1. We find some heterogeneity in the price response across quantiles. The news shock compresses the price distribution: the shift in demand is more pronounced for high-value properties (-0.035 for the 10% quantile versus -0.045 for the 90% quantile). This differential variation within LSOAs may reflect differences across differentiated housing markets. Richer residents (or buyers of high-value properties) may have a high willingness-to-pay for environmental quality and the news shock thus affects their valuation of a neighborhood disproportionately. These agents may also differ in their access to information, i.e., in the precision of their pre-disaster priors and in their capacity to process the Fukushima signal, or they may differ in their mobility. Our findings would be consistent with richer households valuing environmental amenities more, better processing the news shock, or being less subject to relocation frictions.

Comparison with the literature Overall, we find that the Fukushima accident generated a large, persistent shift in housing demand in at-risk areas of England. This finding contrasts with recent studies finding either a non-significant effect on housing prices in the United States and Sweden (Fink and Stratmann, 2015; Ando, Dahlberg, and Engström, 2017), or a large but very short-lived effect in China (see Zhu et al., 2016, for an analysis based on land primary market), or an impermanent effect in the immediate neighborhood of U.S. nuclear facilities (Tanaka and Zabel, 2018). The estimates that are closest to ours come from two European countries, Germany (Bauer, Braun, and Kvasnicka, 2017) and Switzerland (Boes, Nüesch, and Wüthrich, 2015). This large disparity across environments may relate to features that are context-specific, for instance, the functioning of housing markets, the insurance coverage, risk preferences or the policy response from the government. The latter underlies the findings of Bauer, Braun, and Kvasnicka (2017): the German government planned a phasing out of nuclear power with large expected employment effects at the local level. We provide below a sensitivity analysis of these findings, including an investigation of possible employment effects.

3.2 Sensitivity analysis and policy uncertainty

Sensitivity analysis We provide a sensitivity analysis in Section C of the online Appendix, in which we test for pre-existing differential trends and we examine whether there is a return to the mean in the aftermath of the news shock. We find no evidence that the effect was limited to a short-lived period of uncertainty. In effect, the price drop is larger after December 2012, possibly reflecting an announcement effect following the contract renewal of some nuclear plants.

We also consider the following alternative assignments of treatment across LSOAs: (i) we select control LSOAs within the neighborhood of non-nuclear power plants; (ii) we vary the 20-km cut-off between the treated and control zones within the 0-100-km radius of a plant, and we vary the outer radius defining the control area; (iii) we consider 'doughnut' specifications with a buffer between treated and control areas, (iv) we study the response of housing markets in the neighborhood of nuclear *waste sites*. We also consider specifications with controls accounting for trends along LSOA characteristics (e.g., environmental awareness, housing quality, geography), differential dynamics of housing demand across commuting zones, and high-quality transaction characteristics using Nationwide data. This sensitivity analysis provides strong support for the baseline findings of Table 2.

Employment, risk perception and policy uncertainty Our favored interpretation is that the shift in housing demand results from a revision of beliefs about nuclear risk. An alternative channel relates to policy uncertainty, and the possible closure of nuclear facilities and their subsequent local employment effects.

To assess the possible role of policy uncertainty, we explore treatment heterogeneity across nuclear power plants in Section C of the online Appendix.[25] In particular, we investigate whether the price response depends on the relative size of the nuclear plant in the local economy, as proxied by the ratio between workers employed by the nuclear plant and the total active population within the evacuation zone. We find that the hedonic price response is slightly lower around more "influential" nuclear power plants, which would be inconsistent with fears of phasing-out and their associated employment effects (as observed in Germany, see Bauer, Braun, and Kvasnicka, 2017). Two results cast further doubt on the importance of policy uncertainty in explaining the baseline findings: (i) while the renewal of some nuclear facilities was only announced at the end of 2012/beginning of 2013, we do not observe any price rebounds afterwards; (ii) there is a price response around nuclear waste sites despite their negligible economic influence.

4 Anchoring role of mobility rigidities

In the previous section, we quantify the average hedonic price response in at-risk areas. Some elements, however, hint at treatment heterogeneity; for instance, the larger response observed for higher price quantiles. In this section, we further investigate treatment heterogeneity. We proceed in three steps. We first discuss the theoretical intuition governing the differential response in housing demand and residential dynamics to a similar amenity shock. We then construct empirical measures of mobility rigidities at the neighborhood level, and we show how the extent to which residents and workers are able to relocate affects the shift in housing demand in the aftermath of Fukushima. Finally, we document the more secular evolution of neighborhoods affected by an environmental disamenity. To do so, we use information on nuclear plant openings in the 1970s and describe residential sorting and deprivation dynamics in the subsequent decades.

[25] In Section D of the online Appendix, we provide supporting evidence for a change in ecological preferences in treated locations, but no impact on: public transfers towards treated locations; local authority expenditures; the voting behavior of local MPs at the Parliament.

4.1 Theoretical intuition

The capacity of workers and residents to adapt their housing demand to economic conditions or local environmental amenities depends on frictions in housing markets, but also on mobility rigidities as induced by demographics, the local commuting patterns or the ability to find a new job in another location.

We rely on the framework of Monte, Redding, and Rossi-Hansberg (2018) to describe the theoretical intuition underlying the variation in the response of the housing demand to a local shock.[26] Monte, Redding, and Rossi-Hansberg (2018) model the interaction of labor demand and commuting/mobility costs in a New Economic Geography framework where workers can relocate but also commute between the workplace and the place of residence. A local labor demand shock is differently met, depending on the capacity of firms to employ commuters from nearby locations. In the model, (i) a shock affects the desirability to work in a location or a set of nearby locations—this could be modeled as a negative productivity shock and would reduce the utility flow received by workers, (ii) the shock triggers an adjustment in the location of workers and residents, (iii) this relocation/adjustment in demand is amplified through agglomeration spillovers or preference spillovers (peer effects). Monte, Redding, and Rossi-Hansberg (2018) highlight the importance of commuting costs in shaping the previous sequence of effects: with large commuting costs, the choices of workplace and place of residence are closely tied, limiting the capacity of agents to adjust housing demand and labor supply independently.

We interpret this intuition in the context of the framework described in Section 2. We assume that locations are imperfect substitutes for residents because of idiosyncratic preferences for neighborhoods, but also because these residents are workers and have different values tied to different location-specific jobs. In the presence of commuting costs, rigidities in housing markets will induce sluggishness in the adjustment of labor supply. Reciprocally, labor market frictions will temper movements in housing demand (Caliendo, Dvorkin, and Parro, 2019). The set of decent outside relocation options is both disciplined by available places of residence and available job vacancies. One consequence is that the shift in housing demand will be smaller in at-risk areas where workers are less mobile due to the nature of their job.

[26] Lee and Lin (2018) develop a stylized model of residential sorting in which the fluctuations in housing demand depend on the interaction between permanent amenities and temporary amenity shocks. Intuitively, higher dispersion in permanent amenities across neighborhoods generates a more persistent spatial distribution of individuals over time and limits the impact of temporary shocks. The rank of a neighborhood with desirable permanent amenities would be left relatively unchanged; housing demand would be hardly affected by temporary amenity shocks. In short, permanent amenities in at-risk areas, e.g., public infrastructure or natural amenities, anchor neighborhood composition and property values.

Testing this hypothesis requires, in particular, to construct a proxy for the extent to which local residents can find a job while relocating to safer locations. We will rely on imperfect measures of local job mobility, as induced by the LSOA industrial structure. A large number of forces may underlie sectoral differences in job mobility in the United Kingdom: (i) the geographic spread of labor markets (Manning and Petrongolo, 2017) and the geographic dispersion of occupations and geographic specialization (e.g., related to local infrastructure or geographical features), (ii) the accumulation of match-specific capital (Jovanovic, 1979), (iii) the differential thickness of sector-specific labor markets (Şahin et al., 2014). We do not take a stance behind the nature of these industry-specific factors, and only rely on the intuition that the set of substitute locations should be lower in LSOAs where residents work in low-mobility industries—because the limited geography of jobs interacts with their residential preferences. We will also construct similar proxies for migration and commuting patterns, based on the observed behavior of residents.

4.2 Relocation rigidities

Local production Rigidities in labor markets should exert an anchoring force for households and limit the amplitude of fluctuations in housing demand following local shocks. This theoretical intuition could explain a previous result on the lower price response in the neighborhood of larger nuclear facilities (see Section C of the online Appendix): the nuclear plant itself ensures a minimum level of economic activity.[27]

To measure the extent to which areas retain residents due to local job characteristics, we rely on the industrial structure of the local labor force. Booth, Francesconi, and Garcia-Serrano (1999) document variation in job mobility across industries. Light manufacturing, distribution, and finance are sectors with high job mobility. In each LSOA, we measure the census shares of workers in industries with a high level of job mobility, in 1971 (*Mobility, ind-1971*) and in 2011 (*Mobility, ind-2011*). Similarly, for each LSOA, we compute the share of workers in occupations with high job turnover in 2011 (*Mobility, occ-2011*).[28]

We estimate treatment heterogeneity along local job mobility in Table 3; we identify the role of job mobility by augmenting Equation (1) with the interaction of the treatment variables and *Mobility (ind-2011)*. All equations include LSOA fixed

[27] There are consistent coagglomeration patterns around nuclear plants, typically in sectors such as Utilities and Construction. Usually, the presence of a nuclear plant guarantees the presence of highly-skilled and well-paid engineers and physicists.

[28] In Booth, Francesconi, and Garcia-Serrano (1999), various characteristics (gender, age, and the date of entry into the job market) also impact job mobility. However, LSOA populations are quite homogeneous along these dimensions, while there is large spatial dispersion in industrial structure.

Table 3. The role of neighborhood characteristics—industry composition in 2011.

	Transaction prices				Deprivation
	(1)	(2)	(3)	(4)	(5)
Treatment	.2250	.2315	.2160	.1729	.0510
	(.0340)	(.0393)	(.0340)	(.0322)	(.0131)
Treatment	-.5796	-.4848	-.5923	-.4192	-.1567
× Mob. (ind-2011)	(.0746)	(.0683)	(.0750)	(.0694)	(.0282)
	[-.0313]	[-.0262]	[-.0320]	[-.0226]	[-.0083]
Treatment		-.1004			
× Mob. (occ-2011)		(.0472)			
		[-.0063]			
Treatment			.0187		
× Mob. (ind-1971)			(.0181)		
			[.0028]		
Treatment				-.0134	
× Deprived				(.0074)	
				[-.0067]	
Treatment				.0030	
× Rural				(.0054)	
				[.0015]	
Treatment				-.2364	
× Unemployment				(.1096)	
				[-.0094]	
Observations	3,739,200	3,739,200	3,738,459	3,739,200	110,545

Note: Standard errors, clustered at the LSOA × month level, are reported in parentheses in columns 1-4. Robust standard errors are reported in parentheses in column 5. Standardized effects are reported between square brackets. Each column displays the result of a separate regression. The unit of observation is a transaction in columns 1-4. The unit of observation is an LSOA × year in column 5. We only report the coefficient before the spatial treatment interacted with a post-Fukushima dummy and the coefficient(s) before the triple interaction (i.e., the coefficient before the spatial treatment interacted with a post-Fukushima dummy and the neighborhood variable(s)). All specifications include post-Fukushima dummy × zone dummies and LSOA fixed effects. Transaction characteristics/LSOA deprivation score interacted with a post-Fukushima dummy are added as controls in columns 1-4. *Mobility (ind-2011)* is the share of workers in (light) manufacturing, distribution and finance in 2011. *Mobility (occ-2011)* is the share of managers, professionals, clerks and self-employed in 2011. *Mobility (ind-1971)* is the share of workers in (light) manufacturing, distribution and finance in 1971. These industries/occupations have been selected following Booth, Francesconi, and Garcia-Serrano (1999) (see Section 4). *Deprived* is a dummy for neighborhoods with a deprivation score above the median. *Rural* is a dummy for rural LSOA. *Unemployment* is the LSOA unemployed rate, i.e., the number of unemployed residents divided by the number of active residents.

effects and the set of extended controls, but we only report the coefficient before the treatment and the "heterogeneity coefficient" before the triple interaction. An additional percentage point in the share of the labor force employed in high-mobility industries increases the price drop by 0.58 percentage points (a standardized effect of -0.031). A neighborhood in the top decile of job mobility experiences a price decrease of about -8.8% versus -1.2% for a neighborhood in the bottom decile. This estimate is robust to the addition of interactions between the treatment and (a) the *occupational* structure of the labor force, (b) the share of high-mobility industries in 1971 (column 3), and (c) interactions of the treatment with other LSOA characteristics such as the deprivation score, the unemployment rate, and a dummy for rural LSOAs (column 4). More specifically, when we allow treatment effects to vary with the share of workers in high-turnover occupations, we find that an additional percentage point in the high-mobility occupational share only marginally amplifies the price response. A possible explanation is that industries are better predictors of job mobility than occupations (Booth, Francesconi, and Garcia-Serrano, 1999). By contrast, we do not find treatment heterogeneity along industrial composition as measured in 1971 (column 3). Finally, deprivation and unemployment are weak predictors of treatment heterogeneity (column 4).

These findings suggest that the presence of industries with low job turnover before the news shock is the crucial factor that exerts an anchoring effect on demand for housing. In column 5 of Table 3, we look at the heterogeneity in treatment effect on neighborhood composition: one standard deviation in the job mobility measure adds -0.0083 to the decrease in deprivation rank induced by the treatment (versus an average treatment effect of -0.02).

Table 4. The role of neighborhood characteristics—commuting and moving costs.

	(1)	(2)	(3)	(4)
Treatment	-.0795	-.0851	-.0364	.0058
	(.0070)	(.0156)	(.0040)	(.0064)
Treatment × No commute	.2046			
	(.0236)			
	[.0200]			
Treatment × Children		.2076		
		(.0738)		
		[.0101]		
Treatment × Social housing			-.0568	
			(.0275)	
			[-.0059]	
Treatment × Migration				-.3945
				(.0613)
				[-.0269]
Observations	3,637,296	3,739,200	3,739,200	3,739,200

Note: Standard errors, clustered at the LSOA × month level, are reported in parentheses. Standardized effects are reported between square brackets. Each column displays the result of a separate regression. The unit of observation is a transaction. We only report the coefficient before the spatial treatment interacted with a post-Fukushima dummy and the coefficient before the triple interaction (i.e., the coefficient before the spatial treatment interacted with a post-Fukushima dummy and the neighborhood variable). All specifications include post-Fukushima dummy × zone dummies, LSOA fixed effects and transaction characteristics/LSOA deprivation score interacted with a post-Fukushima dummy. *No commute* is the share of individuals working in the same LSOA ("co-workers") who are living in the treated zone. *Children* is the average number of children per household. *Social housing* is the share of residents living in council housing. *Migration* is the share of migrants (outmigrants and immigrants, i.e., residents with different addresses between 2010 and 2011, only one of which being within the LSOA) over the LSOA population in March 2011.

Mobility costs We now explore treatment heterogeneity along other sources of relocation rigidities. The previous section has shown that labor search frictions affect the extent to which agents adjust housing demand. Commuting costs imply that the choice of residence is more or less loosely tied to the choice of job. The adjustment in housing demand following Fukushima should be most pronounced in locations where residents can relocate to safer, nearby locations while retaining their current job. In order to test this hypothesis, we consider a *No commute* variable, which is defined as the share of "co-workers" (people working in the same LSOA, as calculated from the 2011 Census) who live within at-risk areas. Commuting costs are indirectly revealed through the average commuting patterns to a supposedly fixed point: the workplace. A high share of "co-workers" within at-risk areas indicates that commuting costs are too high for households to commute from safer areas. As reported in column 1 of Table 4, the shift in housing demand is higher where a lower share of co-workers lives within the at-risk area.

We then assess the role of demographics and housing conditions in shaping relocation rigidities. In column 2, we look at the average number of children per household as reported in the 2011 Census. Families with children are likely to face higher relocation costs; the treatment effect is indeed smaller when the average number of children per household is higher. In column 3, we look at the share of residents living in social housing as an imperfect proxy for housing tenure arrangements; housing demand is found to respond more in locations with a higher share of residents in council housing. Migration costs may be indirectly revealed by past migration. We construct the rate of migration in and out of the LSOA, i.e., the ratio of residents with different addresses between 2010 and 2011 (only one of which being within the LSOA) to the population in 2011. In column 4, we show that this indirect proxy for lower relocation cost predicts a much higher treatment effect. One standard deviation in the migration rate further lowers housing prices by 2%.

Discussion We find non-negligible treatment heterogeneity along relocation rigidities as induced by job frictions, and commuting and migration patterns.[29]

One would argue (rightfully) that the local production structure is an endogenous

[29] We investigate other dimensions of treatment heterogeneity in Section C of the online Appendix, using measures of local consumption amenities and geography. We find little evidence of treatment heterogeneity along the following dimensions: public services, natural amenities and pollution, elevation, distance to shore, and orientation with respect to the nuclear plant. While being crucial in Lee and Lin (2018), natural amenities account for a much lower degree of persistence in house prices across neighborhoods in our context. In a horse race including the previously-discussed factors, the main predictive factors are the measure of industrial job mobility, the proxy for commuting patterns out of the at-risk area, and previous migration in and out of the LSOA.

factor which responds to local economic conditions, residential composition and amenities. The previous analysis considers that the local industrial structure is slow-moving, thereby contributing to relocation rigidities and persistence in housing demand across space. Relocation rigidities introduce sluggish dynamics through which neighborhood composition and production slowly adjust to an amenity shock. In the longer run, however, the local production and residential composition could adjust markedly to an amenity shock thereby triggering a large range of spatial spillovers. The endogenous amenities and peer effects should play an important role along these sluggish dynamics, by adjusting to the slow-moving composition of neighborhoods.

The next section provides a more descriptive analysis of the residential flight triggered by nuclear risk and fueled by these local endogenous amenities.

4.3 Long-term dynamics and residential flight

The previous analysis sheds light on the adjustments of housing demand and residential composition to an environmental shock. The empirical framework, based on the identification of the treatment effect in the short-run, may imperfectly capture the equilibrium adjustments in the longer run. In the endogenous dynamics of residential sorting and firm location choices, various spillovers may play a role. The increased deprivation in at-risk areas—due to the departure of richer households—should reduce the provision of local endogenous amenities (Kuminoff, Smith, and Timmins, 2013) and affect household welfare through local peer effects (Durlauf, 1996, 2004) or homophily (Schelling, 1971). Firms reliant on a highly skilled and mobile labor force may exit or relocate. Through these different spillovers, a modest amenity shock may lead to persistent spatial disparities in the income distribution.[30]

In this section, we analyze the dynamics of residential composition following the opening of nuclear facilities in the 1970s. The shock is probably not exogenous to the subsequent dynamics: the choice of locations for nuclear facilities is not random, and the installation of nuclear facilities induces positive employment effects. However, and in contrast with the previous section, we can describe the long-term impact of this shock. We test the following hypotheses: in the long run, (i) opening a plant increases deprivation in at-risk areas, and (ii) this effect should be stronger in those at-risk neighborhoods with lower relocation rigidities.

To provide evidence of secular changes in the vicinity of nuclear plants, we an-

[30] Heblich, Trew, and Zylberberg (2018) document that current within-city income inequalities in England are largely explained by differences in exposure to air pollutants before the Clean Air Acts of 1952 and 1968.

alyze how the distance to nuclear plants impacts population size and deprivation over the period 1971–2011. We estimate a difference-in-differences regression in which the spatial treatment for LSOA l, T_l, is interacted with Census year dummies (1971, 1981, 1991, 2001, 2011). The dependent variable is either the standardized population size or the standardized share of low-skilled workers.[31] The reference year, 1971, corresponds to the early stage in the deployment of nuclear plants in the United Kingdom and all active plants (but one) were already operational in 1991.

We test the first hypothesis: opening a plant is associated with an increase of deprivation in at-risk areas. As shown by the first column of Table 5, the proximity to a nuclear plant did not induce a large population change between 1971 and 1981 but had a detrimental impact on the population dynamics from 1981 onward. The population drop over four decades in treated neighborhoods amounts to about 10% of the average LSOA population. As shown in the second column of Table 5, the share of low-skilled workers in the vicinity of a plant markedly increased between 1971 and 2011, with most of the effect occurring between 1971 and 2001, and stabilizing afterwards. In 2001, the treatment effect represents around one-third of the standard deviation of the distribution of low-skilled workers across LSOAs in 1971.[32] The larger deprivation observed near nuclear plants appears to be explained by a neighborhood sorting *à la* Tiebout (1956) (see Banzhaf and Walsh, 2008; Depro, Timmins, and O'Neil, 2015, for more recent contributions), rather than by the decision to locate nuclear power plants in already-deprived areas.

We then test the second hypothesis: the dynamics of deprivation should be more pronounced in those at-risk neighborhoods with lower labor frictions. The industrial structure was key in understanding the impact of the Fukushima's news shock in 2011; it is also key in understanding the long-term dynamics following plant openings. We separate LSOAs based on their industrial composition in 1971 and define high-mobility LSOAs as those with an above-median share of workers in mobile industries in 1971. Again, we rely on the same classification of industries along job turnover (Booth, Francesconi, and Garcia-Serrano, 1999), but the industrial structure is sufficiently different from the one in 2011 for the two indexes to be quite orthogonal. In Figure 5, we plot the LSOA share of low-skilled workers in 1971 (blue) and 2001 (red) for high-mobility (panel a) and low-mobility LSOAs

[31] Population size and the share of low-skilled workers are computed over areas that are equivalent to the 2011 Census LSOAs and geographic units are thus nested across the different census waves.

[32] Part of the increase in the share of low-skilled workers could be driven by a labor demand surge for low-skilled workers fostered by power plants or suppliers. Two elements contradict this interpretation. First, it is unclear why the industrial fabric around nuclear plants would bias labor demand towards lower-skilled jobs. Second, the population decrease near nuclear plants hints at outmigration flows—biased towards higher-skilled individuals—as the main factor.

Table 5. Nuclear plants and long-term evolution of neighborhoods (1971–2011).

	Low-skilled workers (1)	Population (2)
Treatment × 1981	.0636	-.0463
	(.0220)	(.0354)
Treatment × 1991	.1839	-.1824
	(.0224)	(.0363)
Treatment × 2001	.3307	-.1243
	(.0212)	(.0409)
Treatment × 2011	.2740	-.2430
	(.0250)	(.0391)
Observations	119,245	120,162

Note: Robust standard errors are reported in parentheses. Each observation is an LSOA × wave (1971, 1981, 1991, 2001, 2011). Population and the share of low-skilled workers are standardized variables (within each Census wave). All LSOAs within 100 km from a nuclear plant are included, and we only report the difference-in-differences coefficients, i.e., the coefficient before the treatment (LSOA centroid less than 20 km from a nuclear plant) interacted with year dummies. All specifications include wave × zone dummies which clean for time variation within the 100 km-neighborhood of any nuclear plant. The reference year is 1971.

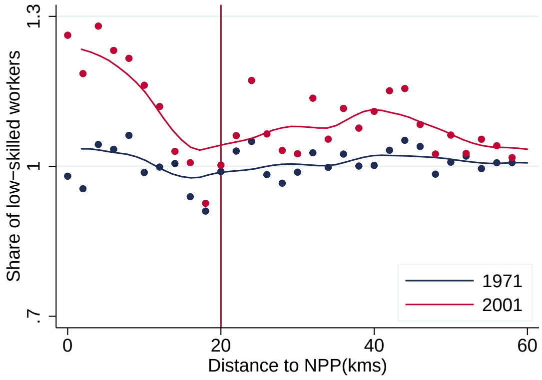
(panel b). While the two types of LSOAs are quite similar in 1971, the situation dramatically changes over the following three decades. We observe a large hump in the share of low-skilled workers around nuclear plants, and this hump is particularly marked within high-mobility LSOAs. In the lower panels of Figure 5, we plot standardized population in 1971 (blue) and 2001 (red) as a function of the distance to the closest nuclear plant for high-mobility and low-mobility LSOAs. Our analysis is nested within 2011 administrative units; by construction, population should be quite constant across LSOAs in 2001. In 1971, however, population may diverge across LSOAs. Our findings indicate large outmigration—as inferred from the difference between population sizes in 1971 and 2001—in high-mobility neighborhoods compared to low-mobility neighborhoods.

These findings support the hypothesis that the persistence of the spatial distribution of income over time depends on the extent to which jobs constrain residential choices. Both our main experimental variation (news shocks in the short run) and the more descriptive long-run analysis of plant openings show that the endogenous response to environmental (dis)amenities may be mitigated by lower job mobility.

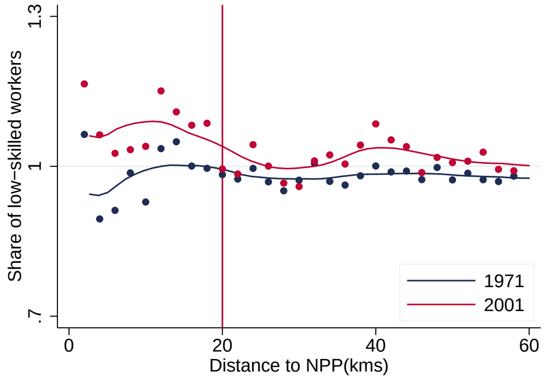
5 Conclusion

We study empirically the impact of a news shock on environmental risk and uncover the following stylized facts: (i) the price response is large, with house prices decreas-

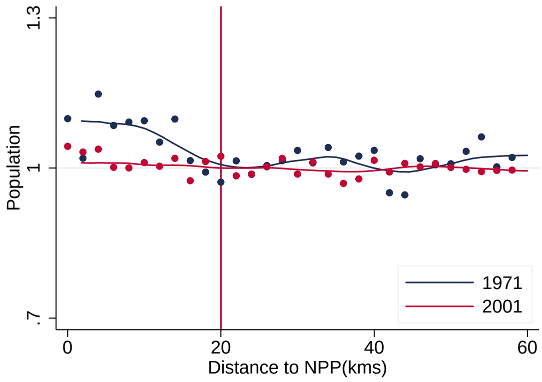
Figure 5. Normalized shares of low-skilled workers as a function of distance to nuclear plants in 1971 and 2001—areas with high- and low-mobility industries.



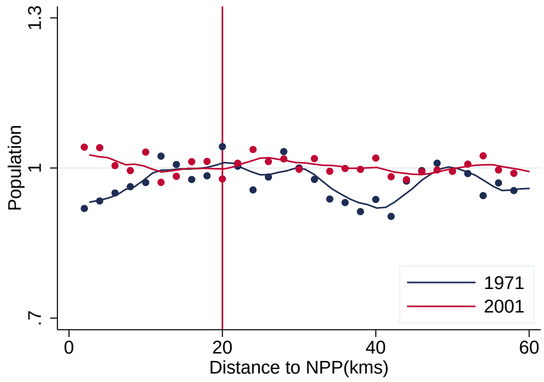
(a) Share of low-skilled workers (high-mobility LSOAs).



(b) Share of low-skilled workers (low-mobility LSOAs).



(c) Population (high-mobility LSOAs).



(d) Population (low-mobility LSOAs).

Note: These figures display the normalized shares of low-skilled workers and total population as a function of distance to nuclear plants in 1971 (dark blue) and 2001 (red) for areas with high- and low-mobility industries. We normalize the shares (resp. population) in 1971 and 2001 by the average shares (resp. population) within each sub-sample. For instance, the shares of low-skilled workers in high-mobility LSOAs (panel a, 1971) are normalized by the average share of low-skilled workers in 1971 across all high-mobility LSOAs within 100 kms of a nuclear plant. Areas with high-mobility industries are defined as having a share of workers in (light) manufacturing, distribution and finance that is above the median among all LSOAs in 1971 (Booth, Francesconi, and Garcia-Serrano, 1999). The share of high-skilled workers is the share of workers in the following one-digit occupational categories: Managers; Professionals; Associate Professionals. The share of low-skilled workers consists of all remaining categories.

ing by 4.2% in the potential evacuation zones of nuclear facilities; (ii) there is an increase in deprivation indicating a flight of richer residents; (iii) the price response depends on the (local) structure of production and relocation/commuting costs.

To understand the long-term implications of these findings, we study the dynamics of residential sorting after the deployment of nuclear facilities in the 1970s. A higher environmental risk—induced by the proximity to nuclear power plants—leads to a flight of richer residents, a process which is mitigated by labor frictions. An environmental disamenity leads to sorting along income. The departure of rich residents may induce lower endogenous amenities which further reduces the desirability of the neighborhood. Along this equilibrium adjustment, spillovers could induce large reversals of fortune and non-negligible spatial inequalities. Labor frictions may mitigate these direct and indirect dynamics (Caliendo, Dvorkin, and Parro, 2019).

These findings shed light on important policy issues. They highlight the interaction between local labor markets and local amenities. Rigidities in labor markets may reduce residential sorting following local shocks to amenities. Such a result illustrates the (possibly beneficial) ex-ante role of place-based policies in mitigating shocks, whereas most of the literature discusses the role of place-based policies in compensating (ex-post) for existing economic shocks (Glaeser and Gottlieb, 2008; Kline and Moretti, 2014; Neumark and Simpson, 2015). Nevertheless, this anchoring role is not necessarily positive: a non-mobile or overly specialized industrial structure may induce large reversals of fortune following aggregate fluctuations, e.g., structural change (Glaeser, Kerr, and Kerr, 2015; Franck and Galor, 2017).

Finally, the paper sheds light on the cost imposed by nuclear power on local communities, but it does not evaluate possible counterfactual policies. Scaling down nuclear programs may lead to higher energy prices (Grossi, Heim, and Waterson, 2017) or a transition back to coal-fired energy production with the associated negative externalities on health (Jarvis, Deschenes, and Jha, 2019) and climate change.

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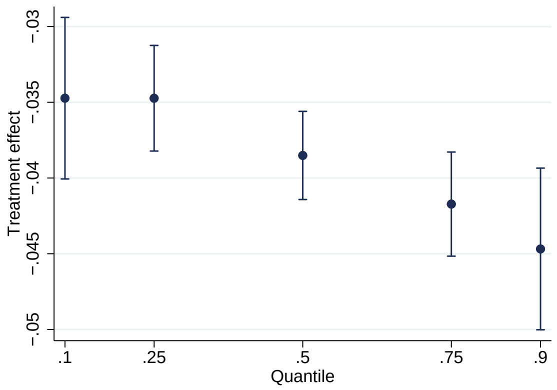
Additional tables and figures

Figure A1. Effect of the Fukushima accident on the housing market—quantile regressions.



Note: This figure reports the difference-in-differences coefficient, i.e., the coefficient before the spatial treatment interacted with a dummy for post-Fukushima, for different within-LSOA quantiles.

Table A1. Effect of the news shock on the number of transactions.

	(1)	(2)	(3)
Number of transactions	-.0102	-.0092	-.0140
	(.0040)	(.0037)	(.0039)
Observations	1,758,055	1,758,055	1,576,378
LSOA fixed effects	No	Yes	Yes
Extended controls	No	No	Yes

Note: Robust standard errors are reported in parentheses. The dependent variable is the number of transactions within an LSOA and a month. Each cell displays the result of specification 1, collapsed at the level of an LSOA × month. We only report the difference-in-differences coefficient, i.e., the coefficient before the spatial treatment interacted with a post-Fukushima dummy. All specifications include post-Fukushima dummy × zone dummies.

Table A2. Effect of the news shock on property values—postcode-level treatment.

	(1)	(2)	(3)
Treatment (postcode)	-.0414	.0005	-.0433
	(.0033)	(.0141)	(.0028)
Observations	3,733,054	3,733,052	3,623,755
Fixed effects	LSOA	LSOA × post	Postcode
Extended controls	Yes	Yes	Yes

Note: Standard errors, clustered at the LSOA × month level, are reported in parentheses. The unit of observation is a transaction. We only report the difference-in-differences coefficient, i.e., the coefficient before the spatial treatment interacted with a post-Fukushima dummy. The spatial treatment is defined as being located within a postcode whose centroid is less than 20 km from a nuclear plant. All specifications include post-Fukushima dummy × zone dummies, and the set of extended controls.